Surficial Processes on Two Fluvially Dominated Alluvial Fans in Arizona

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ABSTRACT

Two active alluvial fans in the tectonically quiescent region of southern Arizona are composed of discontinuous ephemeral stream systems characterized by alternating channelized reaches and sheetflood zones. Channel erosion and overland flow on inactive portions of the fans form new channel reaches with the capacity to divert active flow paths. The distribution and importance of sheetflooding on the fans is strongly controlled by local drainage-basin characteristics and base-level controls. Sheetflooding predominates where sandy bank sediments lead to the development of wide shallow channels, but channelization occurs at the fantoe in areas of long-term base-level lowering. The influence of climate on alluvial-fan formation has often been emphasized in previous studies, but is of only limited importance on active alluvial fans in Arizona.

INTRODUCTION

Detailed studies of alluvial-fan processes have been conducted in arid climates (Beaty, 1963; Bull, 1964a; Hooke, 1967; Harvey, 1984; Blair and McPherson, 1992; Whipple and Dunne, 1992), permafrost regions (Catto, 1993), humid-temperate climates (Kochel and Johnson, 1984; Wells and Harvey, 1987; Orme, 1989), monsoonal climates (Wells and Dorr, 1987), and the tropics (Kesel and Lowe, 1987; Darby et al., 1990; Brierley et al., 1993). These diverse studies have created a general perception that climate is the primary reason for differences in the morphology and physical appearance of alluvial fans. However, the influence of climate on alluvial-fan development is not paramount to tectonics (Bull 1964a), lithology (Harvey, 1984; Catto, 1993), drainage-basin characteristics (Kochel, 1990; Whipple and Dunne, 1992), or storm hydrology (Wells and Harvey, 1987). Alluvial-fan development in most climates is characterized by only a few studies, and even the numerous reports of arid-region fans are almost exclusively of debris-flow dominated fans in California (Beaty, 1963; Bull, 1964a; Hooke, 1967; Blair and McPherson, 1992; Whipple and Dunne, 1992). This spatial bias in the selection of field sites has influenced generalizations made about alluvial fans (Leece, 1990). Modern analogues developed for the interpretation of ancient fan sequences should not be applied until linkages between climate and specific fan characteristics are verified on a full spectrum of fans within a given climate.

In this paper, I document the types and spatial assemblage of facies on two fluvially dominated alluvial fans in southern Arizona in order to establish a more complete representation of alluvial fan processes in desert climates (Fig. 1). Distinct differences in the drainage-basin characteristics of the two fans (Table 1) permit the discrimination of regional and local controls on fan processes. Surficial features associated with two recent floods on each fan provide a unique opportunity to study whether changes in flood magnitude affect process types and distributions. I demonstrate that climate has a relatively limited role in controlling the physical appearance of the fans, casting doubt on broad generalizations about alluvial-fan processes in deserts and other climates.

STUDY SITES

Cottonwood Fan and White Tank Fan are located on the piedmonts of the Tortolita Mountains and White Tank Mountains, respectively, in the Basin-and-Range province of southern Arizona (Fig. 1). Major tectonic activity in southern Arizona ceased approximately three to six million years ago (Menges and McFadden, 1981). Downwearing and reduction of stream gradients since that time in the Tortolita and White Tank Mountains has led to the permanent entrenchment of Pliocene and Pleistocene alluvial fans containing debris-flow deposits. Cottonwood Fan and White Tank Fan are active secondary fans forming at the termini of fanhead trenches passing through the older deposits (Figs. 1 and 2). Sediments on both fans are predominately composed of sand and are derived from similar source-area lithologies (Table 1). Large cobbles and boulders are rare. The thickness of late Holocene deposits exceeds 3 m at the toe of Cottonwood Fan but is less than 3 m on White Tank Fan. Floodwaters on White Tank Fan become reconfined between older surfaces at the fantoe before reaching the alluvial apron on the lower piedmont (Fig. 1b).

The two alluvial fans are located in the arid to semi-arid Sonoran Desert with annual rainfall averaging 28 cm around Cottonwood Fan and 20 cm around White Tank Fan. The surfaces of both fans are well vegetated, especially along the more frequently wetted water courses (Fig. 2). Rainfall at both sites results from three types of weather systems: (1) areally extensive winter westerlies of relatively long duration but low intensity; (2) localized summer monsoonal thunderstorms of short duration but high intensity; and (3) occasional autumn tropical storms of long duration and high intensity. Stronger monsoonal precipitation around the more southerly Cottonwood Fan accounts for the difference in average precipitation between the two locations. Effective discharges on the fans usually last for only a few hours after heavy precipitation in the summer and fall.

Cottonwood Fan and White Tank Fan were chosen for comparison because of distinct differences in their drainage-basin characteristics (Table 1) and physical appearance (Fig. 2). The study of Cottonwood Fan complements an earlier investigation of subsurface facies distributions (Waters and Field, 1986). Initiation of hydrologic gauging on White Tank Fan by the Maricopa County Flood Control District prompted an examination of surficial processes.

METHODS

Surficial facies based on geomorphological and sedimentological features were mapped on

1:300-scale aerial photographs while transecting the fan surface on foot. Channel-wall exposures, limited trenching of White Tank Fan, and previous investigations on Cottonwood Fan (Waters and Field, 1986) were used to determine vertical facies relationships and stratification. Long and cross profiles were measured with an EDM.

The extent of two recent floods on each fan was established from surficial features, historical aerial photographs, and eye-witness accounts. Estimates of peak discharges were made at the fan apices using the slackwater deposit-paleostage indicator technique described by O'Connor and Webb (1988) and Wohl (1992). Manning's roughness values of 0.035 for channels and 0.05 to 0.07 for the vegetated banks were used in the step-back-water modeling. The wide range in discharge estimates presented reflects the uncertainty in step-backwater modeling along wide, alluvial channel reaches.

DESCRIPTION OF FLOODS

Cottonwood Fan. Intense rains on July 24, 1990 precipitated flooding on the fan surface. Although precipitation totals are not available for the drainage basin, one 30-year resident described the thunderstorm as the strongest in memory. Rain gauges in other parts of the region recorded as much as 10.7 cm in a three-hour period (Pima County, 1990). Peak-discharge estimates at the fan apex ranged from 40-50 cubic meters per second (cms). A discharge of 40 cms has an estimated recurrence interval of less than ten years based on synthetic hydrological modeling (Eychaner, 1984). Synthetic 100-year discharge estimates for neighboring drainages in the Tortolita Mountains are substantially larger than any floods that have occurred in the past few hundred years (House, 1991), implying that the actual recurrence interval of the 1990 flood was greater than 10 years. Local residents claim that a flood similar to the 1990 event had not occurred in more than 20 years. The flood produced no significant channel changes.

A much larger flood inundated the fan on September 13, 1962. Rainfall totals exceeded 7.6 cm in a two-hour period with one resident recording 11.7 cm (Rostvedt and others, 1968). A single slope-area measurement was made 8 km upstream of the fan apex and yielded a peak discharge estimate of 161 cms (Rostvedt and others, 1968). The discharge at the fan apex may have been higher, because the storm first saturated the fan and piedmont before moving into the upper drainage basin. A discharge of 161 cms at the fan apex is less than the 100-year synthetic discharge (Eychaner, 1984), but the actual recurrence interval may be greater than 100 years. The fan's northern channel (Fig. 2a) was abandoned during the flood (Field, 1994).

White Tank Fan. A flood of moderate magnitude occurred on the fan during the night of July 24, 1992. A rain gauge located just outside of the drainage basin recorded only 1.9 cm of rain in 45 minutes, but 7.6 cm fell at more distant localities during the extremely spotty storm (Maricopa County Flood Control District, personal communication, 1992). The estimated peak discharge of 20-30 cms at the fan apex has a recurrence interval between 10 and 25 years based on synthetic hydrologic modeling (Alluvial Fan, 1992). The flood caused no significant channel modifications.

Differences in the 1942 and 1953 aerial photographs indicate that a large flood during this time interval resulted in extensive channel widening and migration. Large discharges emanated from the White Tank Mountains during a tropical storm in late August, 1951 (Kangieser, 1969). This areally extensive storm was the most likely cause of the channel changes on White Tank Fan. Paleoflood reconstruction conducted 3.2 km upstream from the fanhead estimated a peak discharge between 57 cms and 114 cms for a flood that occurred during the past 100 years (Alluvial Fan, 1992), probably in 1951. Aerial photographs demonstrate that the 1951 flood was the most significant event in the past 50 years, and synthetic modeling suggests that the actual recurrence interval may be greater than 100 years (Alluvial Fan, 1992). Field (1994) describes in detail the channel modifications resulting from this storm.

SURFICIAL FACIES AND PROCESSES

Two erosional facies (erosional channels and overland flow zones) and two depositional facies (depositional channels and sheetflood zones) are recognized on both fans. Flow depths and directions, topographic expression, plan views, and other surficial features were used to describe and map each facies (Figs. 3 and 4). Subsurface information supplemented the descriptions of the two depositional facies.

There is no surficial or subsurface evidence of debris-flow deposits on either fan. Destabilization of hillslope soils in southern Arizona during the Pleistocene-Holocene climatic change resulted in an increase in debris-flow activity that rapidly tapered off after 8000 yr B.P. (Bull, 1991). Modern rates of weathering are insufficient to produce an abundant supply of sediment for large debris flows (Melton, 1965). Although small debris flows may occasionally occur on steep mountain slopes, they evidently have not reached the apices of Cottonwood Fan and White Tank Fan, located 10.4 km and 4.0 km from the mountain front, respectively.

Erosional Channels. Erosional channels consist of rectangular to v-shaped gullies and swales with relatively low width:depth ratios (Fig. 3). The channels are typically less than 1 m wide and 0.5 m deep but are as much as 3 m wide and 2 m deep. Sediment is not found on the floor of the channels except for intermittent pebble to cobble lags. Upstream, erosional channels end at a vertical headcut or gradually merge with the fan surface (Fig. 3).

Erosional channels form from erosion of the fan surface due to (1) runoff generated by precipitation on inactive portions of the fan, (2) the reconcentration sediment-deficient floodwaters at the margins and distal ends of sheetflood zones, and (3) headward erosion where overland flow reenters established channels. Erosional channels are most prevalent on inactive portions of the fan (Fig. 4)

Depositional Channels. Depositional channels have higher width:depth ratios than erosional channels (Fig. 3). Depostional channels decrease in depth and merge with sheetflood zones downstream. They have vertical to rounded banks and are up to 40 m wide and 1 m deep. Sedimentary sequences deposited on the channel bottoms contain 5- to 30-cm-thick, laterally discontinuous beds of poorly sorted, horizontally laminated, gravelly sands (Fig. 3). Each bed is truncated on top. Cross-stratified sands are locally present throughout but are most common at the top. The total thickness of the sedimentary sequences is less than 1 m on White Tank Fan but occasionally exceeds 1.5 m on Cottonwood Fan. Discontinuous gravel lenses are found in scour pockets at the base of the channel deposits (Fig. 3).

The basal gravel lenses, interpreted as gravel lags, indicate that depositional channels form from the widening and subsequent backfilling of erosional channels. During a flood event the channel bed is initially scoured, truncating earlier deposits. Laterally discontinuous beds later backfill the channel as flow rapidly infiltrates through the highly permeable sands. At the end of the flood, clear-water flow meanders across the channel bed depositing cross-stratified sands in shallow depressions. As channel width increases through bank collapse, the scour depths of successive flows decrease, resulting in a net increase in bed elevation. Consequently, the entire sequence of channel sediments is composed of several truncated beds, each deposited by a single flood.

Sheetflood Zones. Sheetflood zones consist of broad unconfined planar surfaces. The upstream portions of the surfaces are fan-shaped in plan view with flow paths initially radiating away from the apex before reconverging downstream (Fig. 3). Flow depths rarely exceed 15 cm. The largest sheetflood zone on White Tank Fan is 185 m wide and 625 m long. On Cottonwood Fan the maximum width and length are 155 m and 310 m, respectively. Depositional and erosional channels dissect the margin and toe of the sheetflood zones.

Sedimentological features on the surface vary down slope. Depositional channels split into a series of indistinct distributary channels that rarely traverse past the upper third of the sheetflood zones (Fig. 3). Cobble bars radiate away from the apex and preferentially develop behind obstructions such as tree trunks and bushes. Short (up to 5 m) and shallow (less than 0.5 m) scour pockets form downstream of the obstructing vegetation. Gravel bars become finer grained and less prevalent on more distal sheetflood zones. Sand sheets are present downstream of the gravel bars and become finer grained further from the apices of the sheetflood zones (Fig. 3).

Vertical stratification sequences contain 10- to 30-cm-thick, laterally continuous, fining-upward beds of horizontally laminated sands (Fig. 3). Discontinuous gravel lenses are locally present at the base. The total thickness of individual sequences rarely exceeds 0.5 m on White Tank Fan or 1 m on Cottonwood Fan.

The geomorphological and sedimentological characteristics of the sheetflood zones are formed by rapidly decelerating sheets of shallow unconfined floodwater. A sheet of unconfined flood water moving down a slope is termed a sheetflood (Hogg, 1982). Expansion of flow at the apex, evidenced by the radiating pattern of flow directions, leads to deposition of linear gravel bars. Flow separation around trees and bushes enhances flow deceleration and gravel deposition. Linear cobble trains formed upslope of obstructions are a common feature on alluvial-fan sheetflood zones (Blair, 1987; Wells and Harvey, 1987). The rapid deposition of sediment promotes scouring of the surface immediately down slope of the gravel trains. As flow velocities decrease down slope, progressively finer-grained laterally continuous sand sheets are deposited. Blair (1987) also observed a lateral fining of sheetflood deposits away from the central axis. The sediment-deficient floodwaters that remain after deposition of the sand sheets promote shallow dissection of the surface, reconvergence of flow, and formation of channels at the margins and toe of the sheetflood zones. Reconvergence of flow has been observed on natural sheetflood zones (Packard, 1974) and at the toe of distributary areas on experimental fans (Schumm et al., 1987). McGee's (1897) observations of sheetfloods in southern Arizona share many characteristics with the sheetflood zones described here. However, the importance McGee (1897) attached to sheetfloods as agents of erosion is not supported by observations made on Cottonwood Fan and White Tank Fan.

Overland-Flow Zones. Overland-flow zones consist of ill-defined networks of interlocking, narrow, shallow flow paths (Fig. 3). The topographic expression of the overland-flow zones is very subtle and the facies is recognized in detailed cross-sectional profiles and by textural and tonal patterns produced by local disruption of older surficial features. The flow paths emanate from shallow depositional channels and sheetflood zones. Flow paths are deflected around trees, bushes, and low sand and gravel mounds formed by burrowing organisms. The distal ends of the overland flow zones terminate abruptly at headcuts leading into erosional channels or as thin (< 10 cm) linear-to-arcuate accumulations of gravel and sand.

The overland-flow zones form from shallow overland flow generated where floodwaters flow beyond the margins of shallow channels and sheetflood zones. On-fan precipitation produces minor amounts of overland flow as well. The process operating in the overland-flow zones is best described as unconcentrated sheetflow, because sheetfloods are also considered a type of overland flow (Hogg, 1982). The term overland flow is used here, with a limited meaning, so as not to cause confusion between two similar terms. Overbank flow is an inadequate description of the process as much of the overland flow is generated from sheetflood zones where no channel banks exist. The low-velocity, sediment-poor, overland flow initially disrupts older surficial features by stripping a thin layer of sediment. The flow eventually infiltrates below the surface, depositing the thin gravel and sand accumulations. Extensive erosion does not occur unless flow reenters established channels. The ill-defined networks of flow paths may never be occupied in the same manner twice, although well established channels can develop along some paths through headward erosion. Overland flow at the toe of Cottonwood Fan during the 1962 flood flowed in sheets (Rostvedt and others, 1968), probably between the slightly raised linear ridges (Figs. 2a, 4a, and 5).

AREAL EXTENT AND DISTRIBUTION OF FACIES

Although all four facies are present on both fans, comparisons of the areal extent and distribution of facies reveal the following differences: (1) sheetflooding is more prevalent on White Tank Fan and unlike Cottonwood Fan occurs at the fan apex, (2) the relative importance of sheetflooding decreases downfan on White Tank Fan but increases on Cottonwood Fan; (3) moderate discharges on White Tank Fan inundate a larger area than extreme discharges on Cottonwood Fan (Fig. 4 and Table 2). Cross sectional and longitudinal profiles of both fans help illustrate the reasons for these differences (Fig. 5). Two relatively narrow yet deep channels confine floodwaters at the head of Cottonwood Fan (Figs. 2a and 5). The amount of sheetflooding and overland flow increases as floodwaters reach the nearly planar distal fan (Figs. 4a and 5). In contrast, sheetflooding occurs at the apex of White Tank Fan, because the wide shallow channel is unable to contain even moderate discharges (Figs. 2b, 4b, and 5). Flow below the proximal sheetflood zone enters a system of several shallow channels and sheetflood zones (Figs. 4b and 5). Consequently, much of the fan surface is wetted during moderate events like 1992 (Fig. 4b and Table 2), enabling plants to survive over most of the surface (Fig. 2b). Increasing channel depths downfan (Fig. 5) accompany the decrease in sheetflooding and expansion of inactive surfaces (Fig. 4b and Table 2).

The stark differences between Cottonwood Fan and White Tank Fan mask some subtle similarities. Channels and sheetflood zones alternate downstream on both fans in a pattern characteristic of discontinuous ephemeral streams (Figs. 4 and 6), a unique type of stream system first described by Thornthwaite et al. (1942). The discontinuous nature of channels is best displayed on White Tank Fan (Figs. 2b and 4b). The reach between the distal ends of two sheetflood zones is known as a discontinuity (Fig. 6; Packard, 1974). A series of several discontinuities can develop along a single stream (Figs. 4 and 6; Schumm and Hadley, 1957; Patton and Schumm, 1975). On Cottonwood Fan and White Tank Fan discontinuities also occur side by side giving rise to a complex network where overland flow conveys water between adjacent discontinuities (Fig. 4). Headward erosion along paths of overland flow leads to the abandonment of channel reaches and migration of the main channel (Field, 1994).

Discontinuous ephemeral streams are dynamic systems with each discontinuity migrating upstream over time. Concentration of flow into channels at the toe of the sheetflood zones causes headward erosion (Fig. 6). Sediment created during upstream extension of the headcuts promotes channel backfilling downstream and upslope migration of the aggrading sheetflood zones. The stratigraphic result of this process is the deposition of 1- to 3-m, upward-fining sequences with an erosional base (Packard, 1974; Waters and Field, 1986).

The headcuts and sheetflood zones do not necessarily migrate at the same rate. The rate of migration depends on several intrinsic factors which either promote erosion and the migration of headcuts or deposition and the migration of sheetflood zones (Table 3). If a combination of factors provide conditions that favor erosion, channels segments will eventually merge to form a long continuous channel, like those seen at the head of Cottonwood Fan (Figs. 2a and 4a). If on the other hand conditions favor deposition, channel reaches will become short and discontinuous and sheetflood zones will predominate, as on White Tank Fan (Figs. 2b and 4b).

VARIABLES INFLUENCING THE TYPES AND DISTRIBUTION OF FACIES

The various intrinsic conditions that control the relative importance and distribution of processes on the two fans (Table 3) are in turn dependent upon several extrinsic variables operating independent of the alluvial fans (Table 4). Similarities and differences in the types and distribution of facies (Fig. 4 and Table 2) were used to identify links between the external forces and specific fan features. Similarities between the two fans reflect the influence of the regional tectonic and climatic setting. The distinct differences between Cottonwood Fan and White Tank Fan (Figs. 2 and 4) suggest that local variables exert a strong influence on facies distributions.

Tectonic Setting. Tectonic stability in southern Arizona is a significant reason for why debris flows do not occur on Cottonwood Fan and White Tank Fan. In areas where tectonic uplift has ceased, erosion of the mountain headwaters will reduce stream gradients and lead to entrenchment of alluvial fans at the mountain front (Eckis, 1928). Reduced stream gradients in the Tortolita and White Tank Mountains and substantial distances between the fan apices and source areas preclude debris flows from reaching the two fans. The threshold depths needed to keep debris flows moving are easier to maintain in the narrow confines of rapidly rising mountain ranges than on the broad valley floors typical of tectonically inactive piedmonts. Although short periods of debris flow activity are precipitated by climatic changes (Bull, 1991), tectonic stability is an important prerequisite for the development of fluvial fans in desert regions. In tectonically active arid regions, debris flows can remain the dominant process on alluvial fans for hundreds of thousands of years despite significant climatic fluctuations (Beaty, 1974).

Regional Climate. Discontinuous ephemeral streams are characteristic of semi-arid climates where the rapid loss of runoff through channel absorption promotes valley-floor aggradation (Schumm and Hadley, 1957). High sediment yields in semi-arid climates (Ritter, 1986) further enhance aggradation, because greater quantities of sediment enter the stream system than are removed by the limited discharge. Vegetation, as is present on Cottonwood Fan and White Tank Fan (Fig. 2), is a third factor inducing sediment storage along semi-arid streams. Long periods of aggradation steepen stream gradients, triggering entrenchment of the stored sediment (Schumm and Hadley, 1957; Patton and Schumm, 1975). Sediment removed from the eroded reach is redeposited further downstream. In this manner, the distinctive pattern of the discontinuous ephemeral stream emerges with erosional and depositional reaches alternating downstream.

Lithology. An abundant source of fine-grained sediment is necessary for the development of discontinuous ephemeral streams. Granite, granodiorite, and felsic gneiss found in the Cottonwood Fan and White Tank Fan drainage basins weather to sand-, silt-, and clay-sized particles under the semi-arid climate and moister conditions typical of glacial periods. Boulders are rare on the two fans and are derived from Pleistocene debris-flow deposits near the fan apices and along the fan margins. Secondary alluvial fans in southern Arizona are best developed where there is an abundant supply of fine-grained sediment to precipitate aggradation.

Drainage-Basin Characteristics. Differences in the bank composition of channels (Fig. 7) is the principal factor controlling the distribution and importance of facies types on Cottonwood Fan and White Tank Fan. Rapid erosion of the sandy channel banks on White Tank Fan produces wide shallow channels that enable sheetfloods to cover large portions of the fan surface (Fig. 4b). Rapid channel widening can only occur if the bank materials are easily eroded (Graf, 1988). Channel widening on Cottonwood Fan is inhibited by the higher silt and clay content of the bank sediments (Fig. 7). Consequently, flow is confined on the upper half of the fan to two relatively deep and narrow channels (Figs. 2a, 4a, and 5).

The lithology of the Cottonwood Fan and White Tank Fan drainage basins are very similar, so differences in the bank composition of channels are most likely related to differences in drainage-basin characteristics. The apex of Cottonwood Fan is located much further from the mountain front and a greater percentage of the catchment basin drains old piedmont surfaces containing clay-rich soils (Fig. 1 and Table 1). The general fining trend that accompanies the increasing distance from the source area further enhances the finer grained texture of Cottonwood

Fan. In Arizona, the distance between secondary-fan apices and the mountain front has been related to drainage-basin size, with fans with larger drainages located further from the mountain front (Wells, 1977).

Flood Magnitude. Differences in the physical characteristics of the two fans (Fig. 2) do not reflect differences in the magnitude of floods crossing the surfaces. Both fans have experienced extreme discharges of roughly the same size. The 1951 flood on White Tank Fan, with a unit discharge exceeding 3.91 cms per square km, generated a single sheetflood over the entire fanhead region (Fig. 4b), widened numerous channels, and activated large portions of the fan surface. During the 1962 flood on Cottonwood Fan (unit discharge of 4.66 cms per square km), flow in the northern channel was diverted into the preexisting southern channel. No major channel modifications resulted from the diversion, and sheetflooding was restricted to the midfan and fantoe (Fig. 4a). Channel configurations are relatively stable where the silt and clay content of bank materials inhibit erosion (Schumann, 1989).

Subsequent smaller discharges have not significantly altered facies distributions on the two fans. Sheetflooding occurred at the apex of White Tank Fan in 1992 and was restricted to the middle and lower portions of Cottonwood Fan in 1990 (Fig. 4). The major difference between large and small floods on the same fan is the number of discontinuous channel systems receiving flow and, consequently, the percentage of fan area inundated (Fig. 4 and Table 2). The channel system along the northern margin of Cottonwood Fan was active during the 1962 event but not in 1990, because the bed of the southern channel is presently 70 cm below the northern channel at the fan apex (Figs. 4a and 5). On White Tank Fan, channel systems active along the southern margin in 1951 were not operating in 1992 (Fig. 4b) even though the southern margin is at a lower elevation in the midfan region (Fig. 5); the main channel now at the northern edge of the fanhead preferentially directs discharges into the northern discontinuities (Figs. 2b and 4b). Smaller floods on the two fans follow only portions of the channel systems formed and occupied by high-magnitude events.

Sheetflooding occurred closer to the apex of Cottonwood Fan sometime before 1962 (Fig. 4a) and will occur again if existing channels are backfilled through aggradation. While ephemeral streams characteristically aggrade their channels during low discharges, major flows may cause net scour (Bull, 1979). Therefore, sheetflooding at the apex of Cottonwood Fan is less likely to result from a single large flood than an uninterrupted series of low discharges. Short periods with an increased frequency of low-intensity rainfall have been linked to channel filling on alluvial fans (Bull, 1964b). Temporary weakening of the summer monsoons around Cottonwood Fan would increase the relative frequency of low-intensity sediment-charged winter discharges. Since moderate events like the 1990 flood on Cottonwood Fan are able to transport sediment across the entire fan, an almost complete breakdown of monsoonal rains might be needed before facies distributions, but not necessarily individual flow paths, can be altered on Cottonwood Fan. Human-induced increases in sediment supply could have a similar affect, while human-induced increases in stream discharge would lead to channelization and the abandonment of sheetflood zones at the fan apex.

Base-Level Controls. The inselberg at the toe of White Tank Fan (Figs. 1b and 2b) functions as a local base level during periods of high sediment supply to the piedmont. When sediment supply tapers off, the oversteepened toe of White Tank Fan is dissected as the system adjusts to a new base level lower on the piedmont. The well developed tributary drainage system dissecting inactive surfaces at the toe of White Tank Fan (Figs. 2b and 4b) formed in response to "base-level lowering" that accompanied long-term decreases in sediment supply. Several erosional channels at the fan toe captured flow from the 1951 flood and are now linked to the active fan system (Field, 1994). This channelization due to base-level lowering inhibits sheetflooding at the toe of White Tank Fan. The few erosional channels at the toe of Cottonwood Fan (Fig. 4a) are not part of an integrated channel network; they are transient features developed in response to intrinsic conditions associated with discontinuous-ephemeral-stream processes.

DISCUSSION

Previous studies (McGee, 1897; Blissenbach, 1954; Wells, 1977; Waters and Field, 1986) and limited field observations suggest that Cottonwood Fan and White Tank Fan are characteristic of active fans throughout southern Arizona. Although facies types are influenced by regional factors, the importance and distribution of each facies are sensitive to local conditions. As a result, two fans forming in nearly identical tectonic and climatic settings can display marked differences in physical appearance and facies patterns (Figs. 2 and 4). An over reliance on regional explanations for differences in fan characteristics may lead to inaccurate tectonic and climatic interpretations of ancient fan sequences.

This study documents fluvially dominated processes on arid-region alluvial fans in a tectonically stable setting and reveals that the role of climate on alluvial-fan development has been overemphasized in previous studies. Debris flows are often considered characteristic of arid-region alluvial fans (Miall, 1978, Kochel and Johnson, 1984; Nilsen and Moore, 1984; Kesel, 1985; Blair and McPherson, 1992; Catto, 1993). However, the similarity in climate between Arizona and the rest of the Basin-and-Range province of the southwestern United States suggests that tectonic activity, not climate, is the major reason why debris flows are so prevalent on the well studied fans of California. The alluvial-fan literature from humid-temperate climates consists almost exclusively of descriptions of debris-flow dominated fans (Kochel and Johnson, 1984;

Kostaschuk et al., 1986; Wells and Harvey, 1987; Orme, 1989), but the importance of debris flows is as much a product of storm hydrology, lithology, and/or drainage-basin characteristics (Kostaschuk et al., 1986; Wells and Harvey, 1987; Kochel, 1990). The lack of debris-flow deposits on the few previously studied fans in the tropics (Kesel and Lowe, 1987; Darby et al., 1990; Brierley et al., 1993) probably reflects the small sample size more than a distinctive climatic trait. Using the presence or absence of specific depositional processes in ancient alluvial-fan sediments to interpret paleoclimates (for example, Mack and Rasmussen, 1984) appears unwarranted given that 1) certain processes (for example, debris flows) are found in a variety of climates, 2) alluvial fans within the same climate can be formed by different processes, and 3) other factors also exert an influence over fan deposition.

Blair and McPherson (1993) speculate that in many cases ancient fluvial deposits interpreted as distal-fan sequences may actually represent basin-floor river systems, because, they state, no documentation exists of a natural fan with proximal debris flows and distal waterlain deposits. However, this facies pattern has been observed on modern fans during single flood events (Kesseli and Beaty, 1959) and in Quaternary alluvial-fan deposits (Harvey, 1984). Furthermore, fluvially dominated secondary fans located at the distal ends of older fans containing debris-flow deposits create an apparent proximal-debris-flow-to-distal-fluvial facies pattern (Figs. 1a and 2a). This conjunction of secondary and primary fans may be identifiable in the rock record by an abrupt transition from coarse debris to finer grained reworked fan sediments (Heward, 1978). Contrary to Blair and McPherson (1993), Nilsen and Moore (1984) believe that many ancient fine-grained fan deposits may be misinterpreted as basin-floor deposits. Although fine-grained secondary-fan accumulations would be volumetrically unimportant in the rock record, their presence would be a significant marker of tectonic quiescence during the episodic accumulation of thick conglomeratic sequences. These fine-grained deposits should be composed of fining-upward sequences (Heward, 1978) and increase in thickness away from the source area (Bull, 1972), characteristics associated with Cottonwood Fan (Waters and Field, 1986). White Tank Fan illustrates that fine-grained fan accumulations are not necessarily restricted to the distal portions of piedmonts.

CONCLUSIONS

The following conclusions emerge from the comparative study of floods and related surficial processes on Cottonwood Fan and White Tank Fan:

1. debris flows do not occur on either fan, reflecting the tectonic stability of the region;

2. sediments are fine grained as a result of the weathering and erosion of granite, felsic gneiss, and clay-rich alluvial soils;

3. the semi-arid climate promotes the development of discontinuous ephemeral streams on

the fan surfaces, but local factors exert a stronger influence on the relative importance and distribution of sheetflooding and channelization;

4. during each flood, regardless of magnitude, two depositional and two erosional processes operate within or adjacent to one or more discontinuous ephemeral stream systems (Fig. 4);

5. flood magnitude controls the amount of the fan surface inundated by floodwaters but not the types and distribution of facies;

6. sheetflooding on White Tank Fan is more prevalent at the fanhead and decreases in importance downfan (Fig. 4b and Table 2), because the shorter distance to the mountain front results in sandier channel banks and base-level adjustments precipitated dissection of the fantoe;

7. overland flow and channel erosion have a limited areal extent, but are important in initiating diversions of active flow paths;

8. the present distribution of facies appear relatively stable but could be modified by short-term climatic events.

The morphology of Cottonwood Fan and White Tank Fan reflects the combined influence of several external forces. Stressing the role of climate on fan development without understanding the importance of other factors is disingenuous and will lead to misrepresentations of modern fan processes and the misinterpretation of ancient fan sequences. Future studies must identify linkages between controlling variables and fan processes before significant inferences regarding climate are proposed.

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Table 1. Selected drainage-basin characteristics for the two study fans

Alluvial Fan	Total Drainage Area (km)	Drainage Area on Piedmont (km)	Drainage Area on Piedmont (%)	Distance Fan Apex to Mtn Front (km)	Dominant Lithology	Average Annual Rainfall (cm)
Cottonwood Fan	34.54	9.89	29	10.4	Granite Granodiorite	28
White Tank Fan	14.58	2.61	18	4	Gneiss Granite	20

Table 2. Estimated area of each facies and inactive surfaces on different segments of Cottonwood Fan (CF) and White Tank Fan (WTF)

Fan Segment*	Total Area (km)	Area of facies types (%) EC	DC	SF	OL	Inactive Surface (%)
Upper WTF	0.18	0	27	73	<1	<1
Mid WTF	0.81	<1	11	32	2	55
Lower WTF	0.78	1	13	14	<1	72
Total	1.77	<1	14	28	1	57
Upper CF	0.17	<1	28	0	<1	72
Mid CF	0.51	<1	9	18	12	61
Lower CF	0.58	<1	5	19	31	44
Total	1.26	<1	10	16	19	55

Note: EC=Erosional channels; DC=Depositional channels; SF=Sheetflood zones; OL=Overland-flow zones
* Each segment covers one third the radial distance of the fan.

Table 3. Intrinsic variables controlling the rate of headward erosion of headcuts and headward migration of sheetflood zones

Intrinsic Variable	Increase Rate of Erosion	Increase Rate of Aggradation
Hydraulic roughness	-	+
Channel width	-	+
Water:sediment ratio	+	-
Channel gradient	+	-
Vegetation	-	+
Flow velocity	+	-

Note: - = Decrease in value of intrinsic variable; + = Increase in value of intrinsic variable.

Table 4. External variables controlling the types importance and distribution of facies on Cottonwood Fan and White Tank Fan

External Variable	Spatial Importance	Temporal Persistence
Tectonic setting	Regional	Long-term
Climatic setting	Regional	Long-term
Drainage parameters	Local	Long-term
Basin lithology	Local	Long-term
Base-level controls	Local	Variable
Flood Magnitude	Local	Short-term
Climatic variation	Regional	Variable

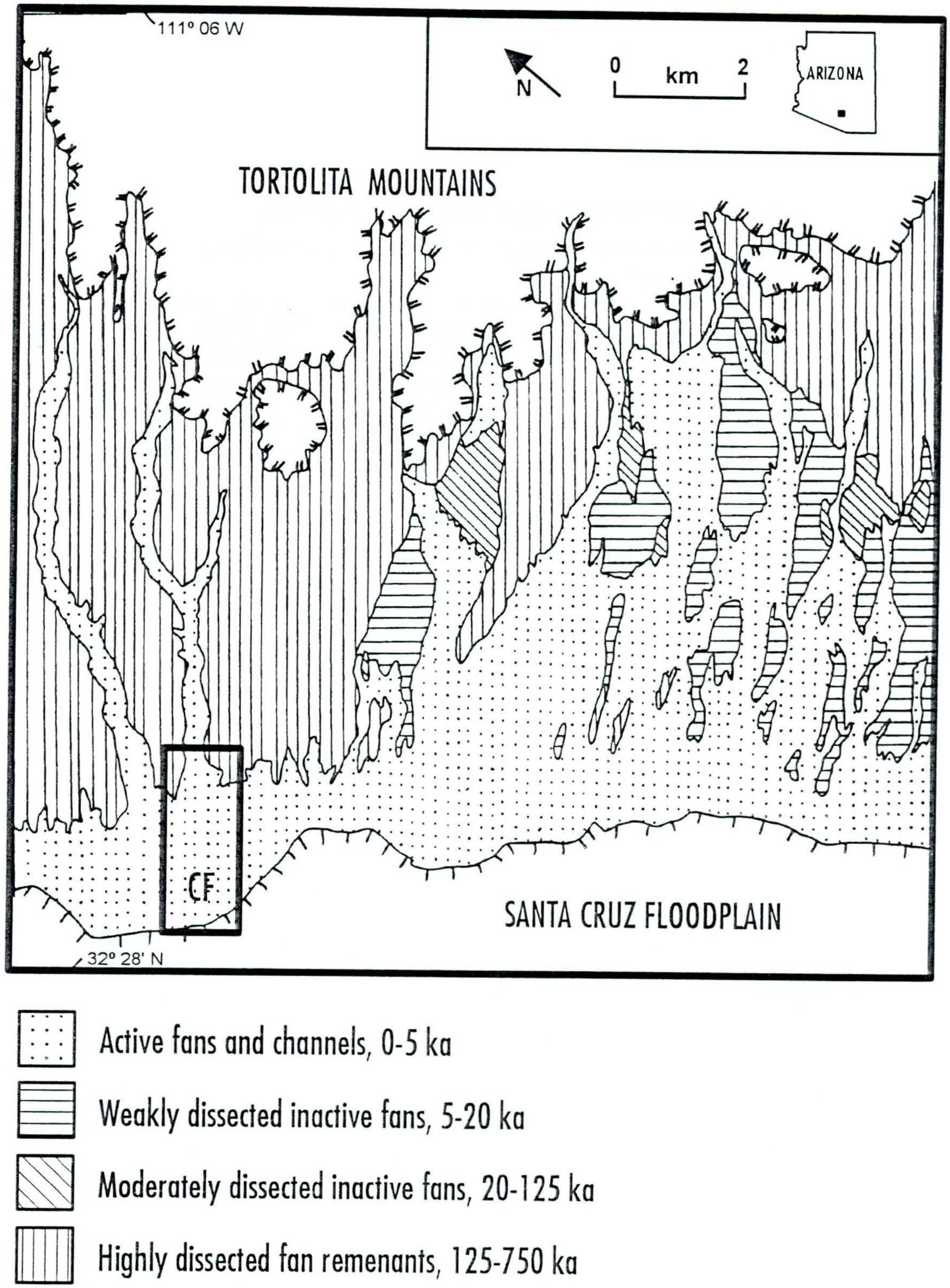


Figure 1a. Simplified geomorphologic map of the Tortolita Mountains piedmont showing the location of Cottonwood Fan (CF).

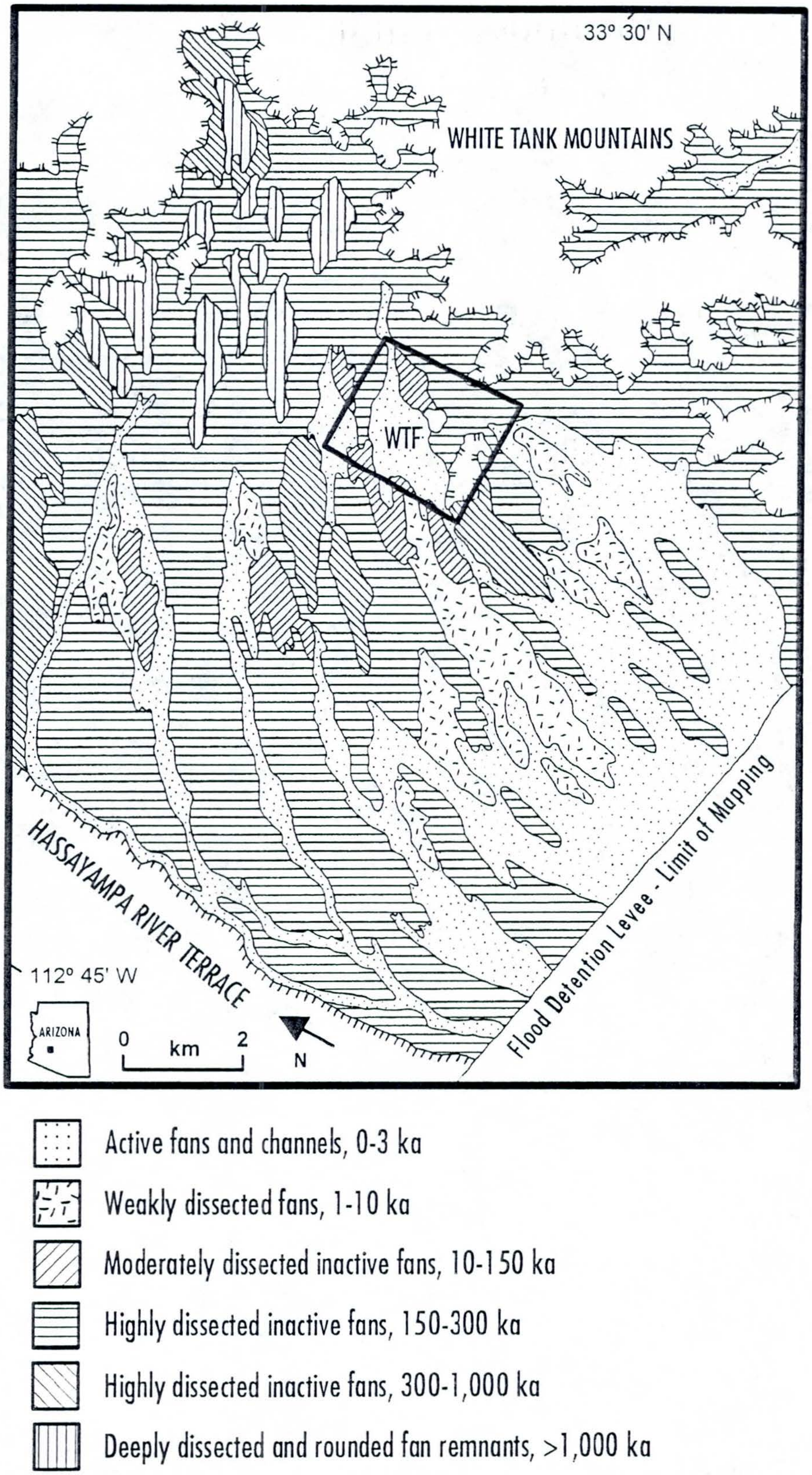
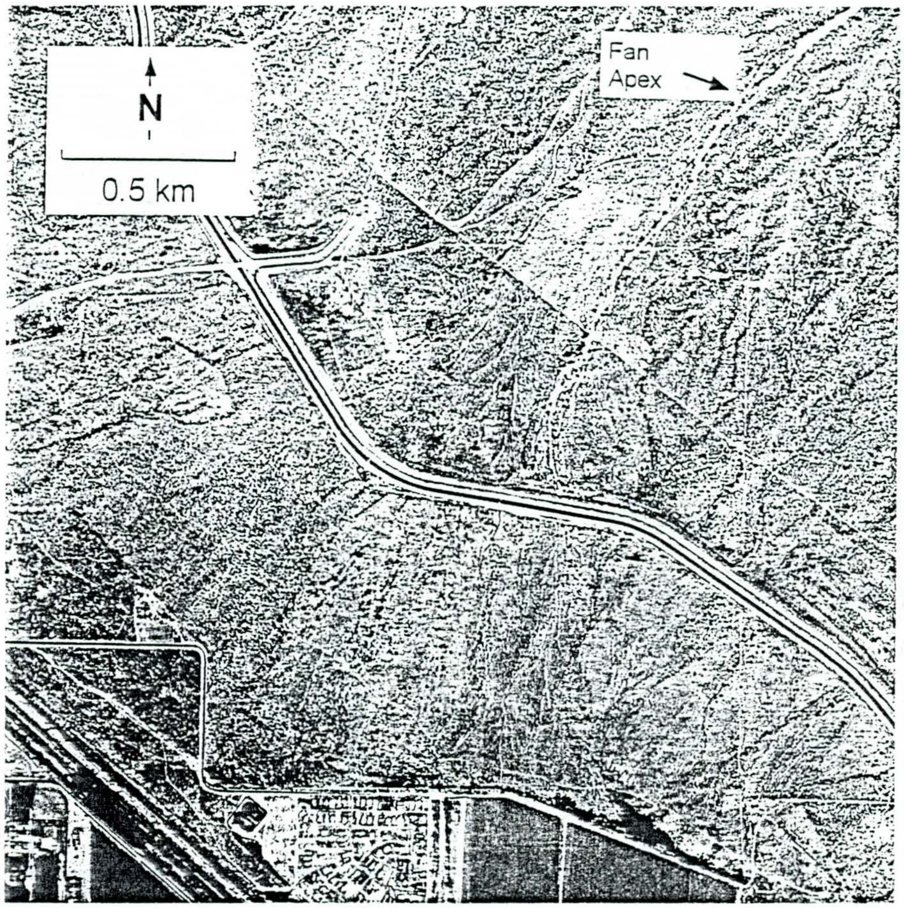
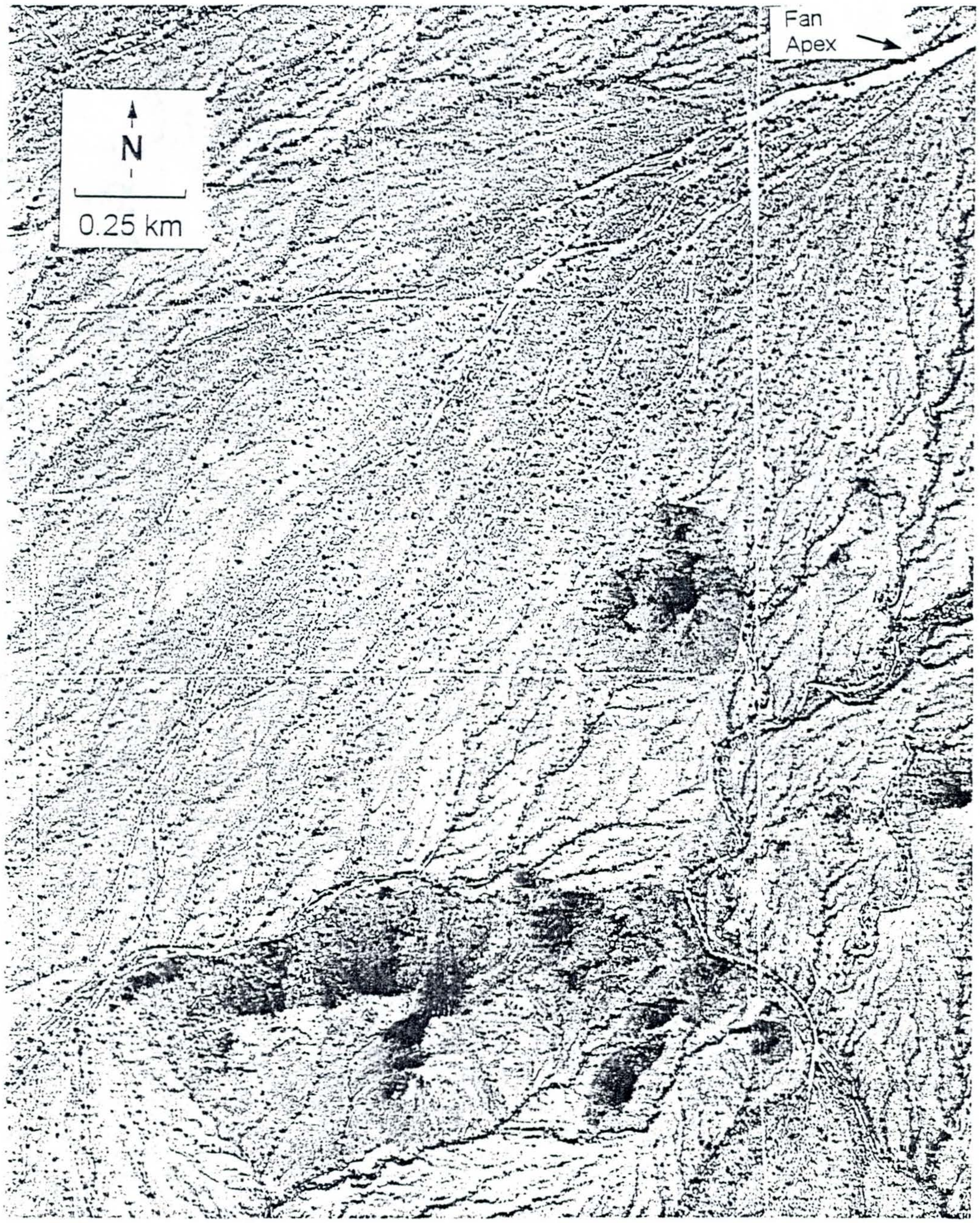


Figure 1b. Simplified geomorphologic map of the White Tank Mountains piedmont showing the location of White Tank Fan (WTF).



a) Cottonwood Fan

Figure 2a. Aerial photograph of Cottonwood fan. Note the older dissected surfaces above the fan apex. The Central Arizona Aqueduct crosses the middle portion of Cottonwood Fan, but natural surficial features remain unaltered above and below the aqueduct.



b) White Tank Fan

Figure 2b. Aerial photograph of White Tank fan. Note the older dissected surfaces above the fan apex.

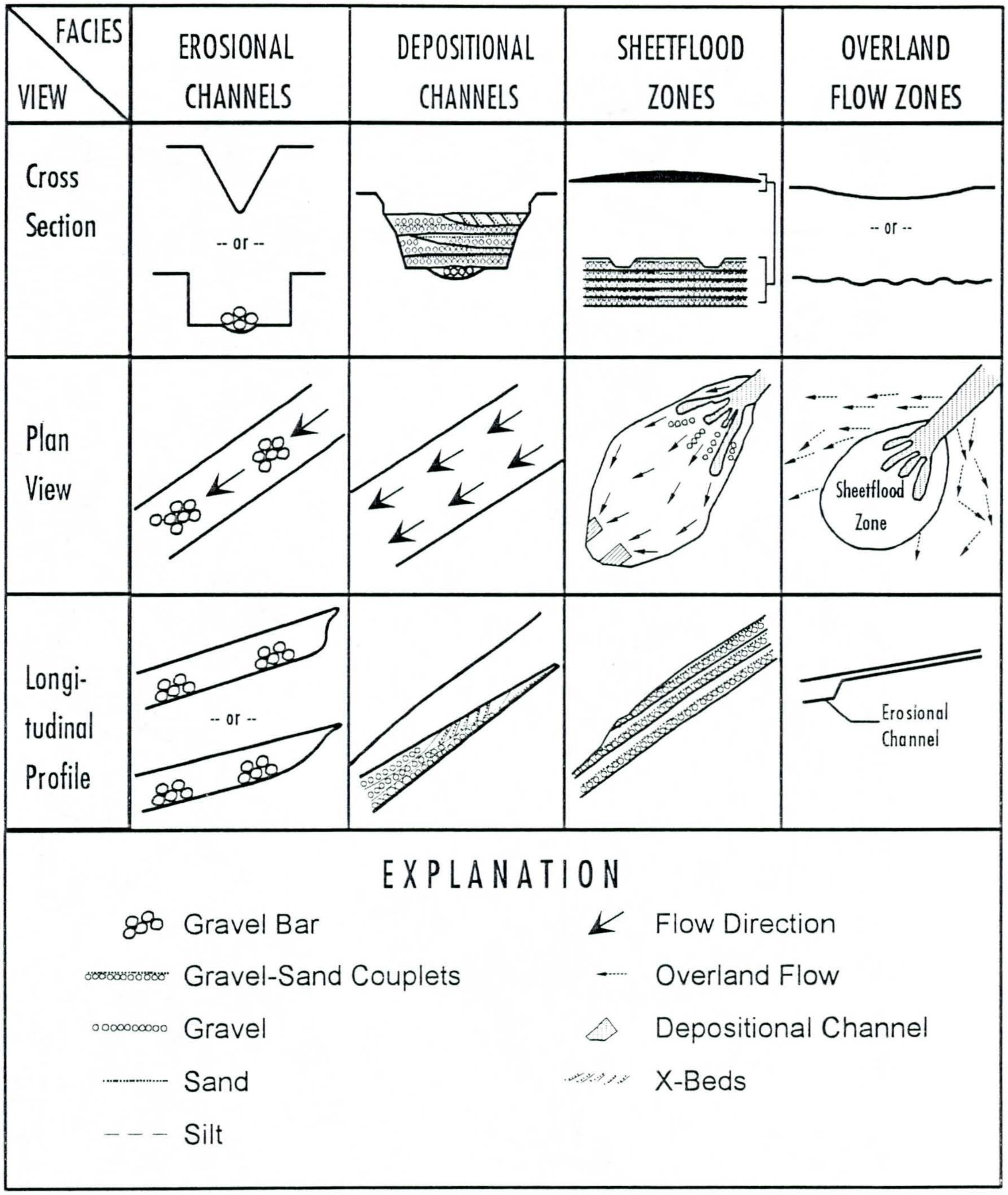


Figure 3. Surficial and sedimentological features of the four facies types found on Cottonwood Fan and White Tank Fan. Sketches not to scale.

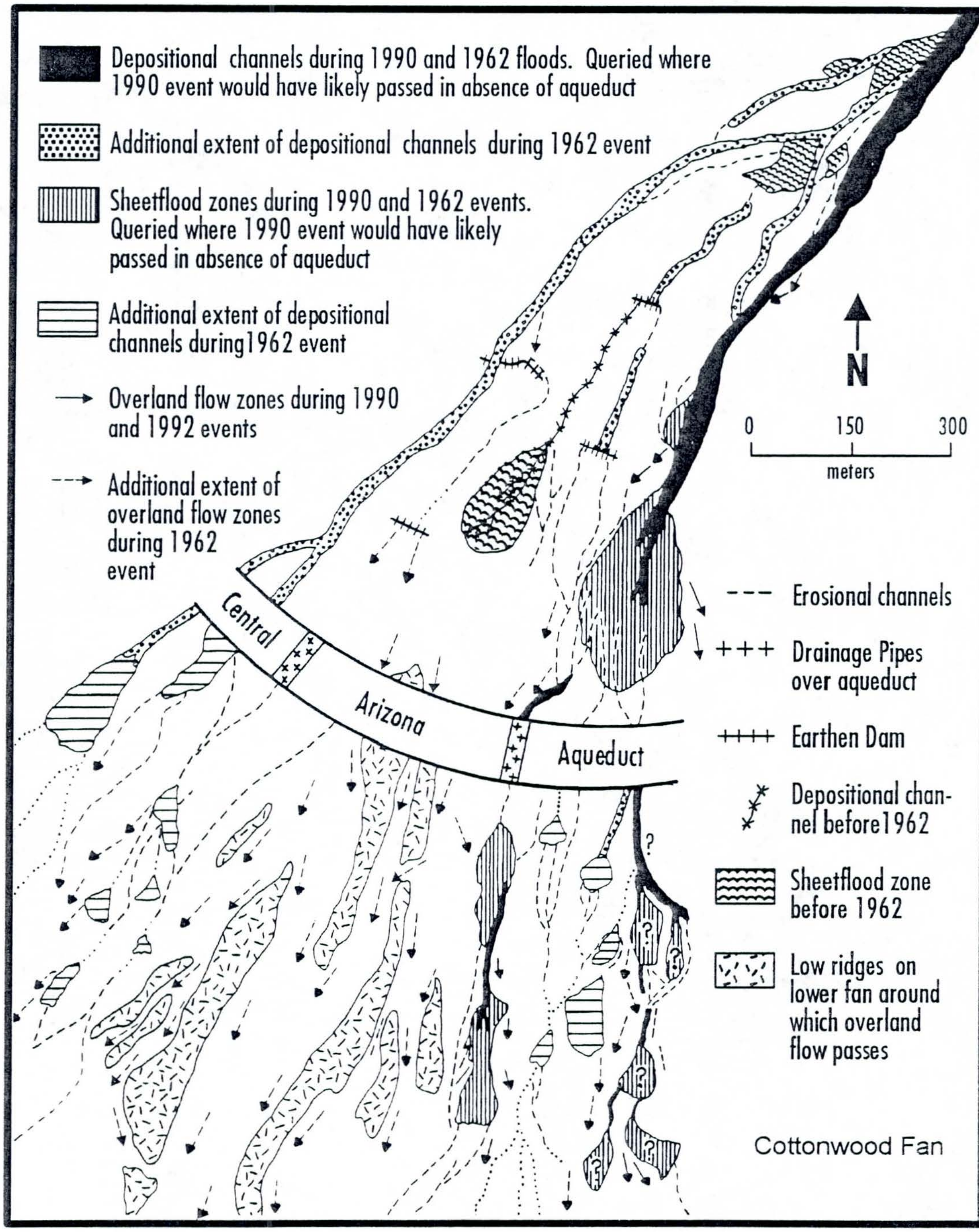


Figure 4a. Detailed facies map of Cottonwood fan showing the distribution of facies resulting from two documented floods. Features formed during earlier floods are also mapped.

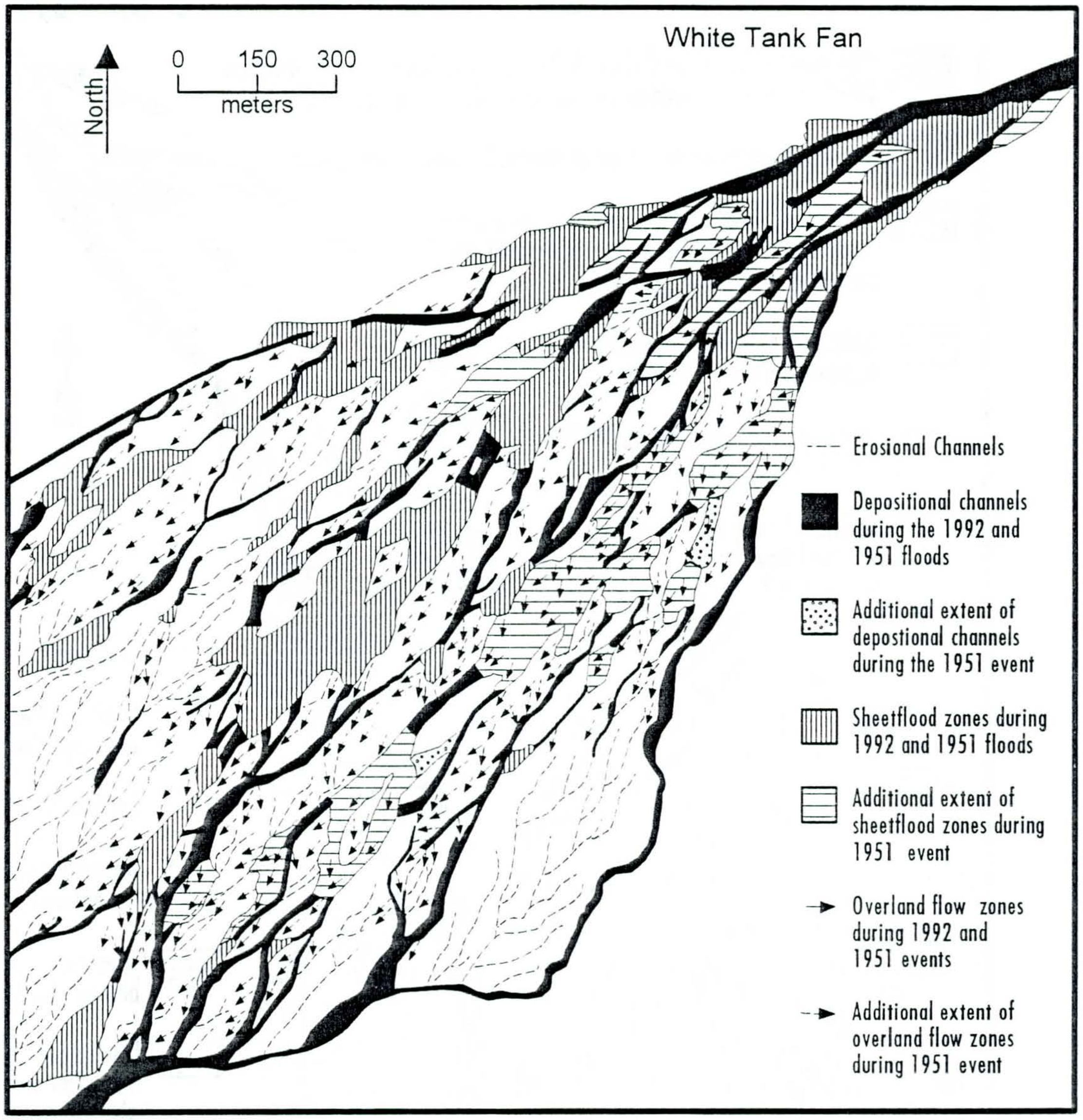


Figure 4b) Detailed facies map of White Tank fan showing the distribution of facies resulting from two documented floods.

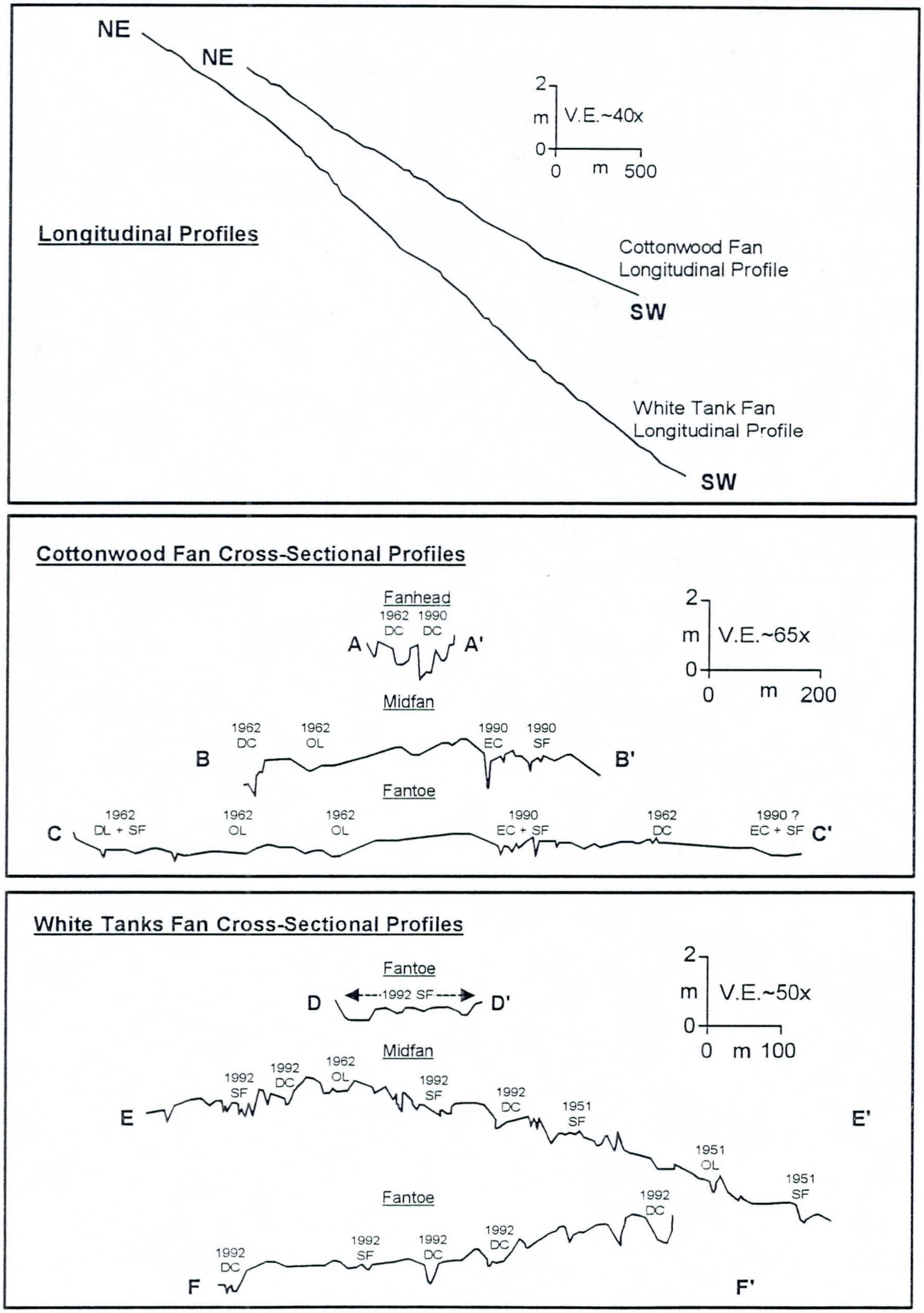


Figure 5. Topographic cross sections and longitudinal profiles of Cottonwood Fan and White Tank Fan showing the areas flooded during the documented floods on each fan. Locations of cross sections are shown on Figure 4. DC=Depositional channel; SF=Sheetflood zone; EC=Erosional channel; OL=Overland-flow zones. Areas inundated by more recent floods were also inundated during the earlier floods.

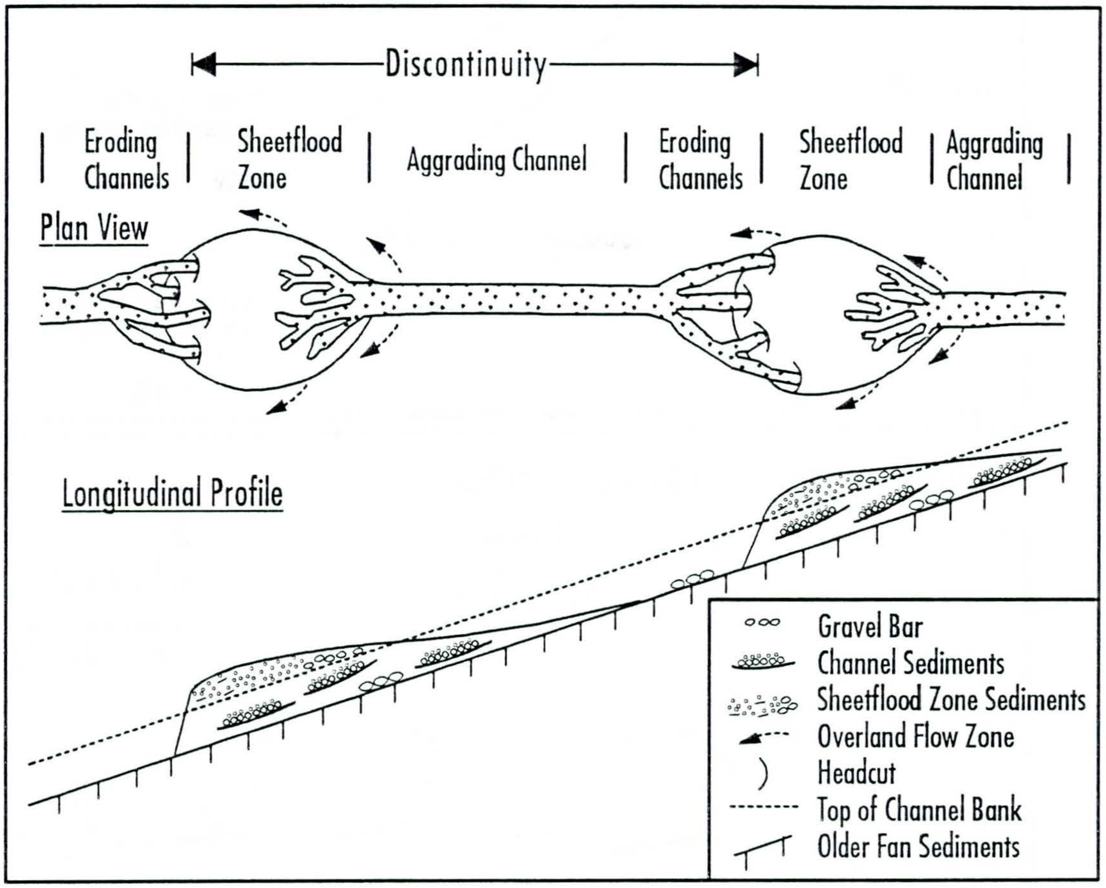


Figure 6. Schematic drawing of a discontinuous ephemeral-stream system showing the relationship between the four facies types. Not to scale. The longitudinal profile is vertically exaggerated.

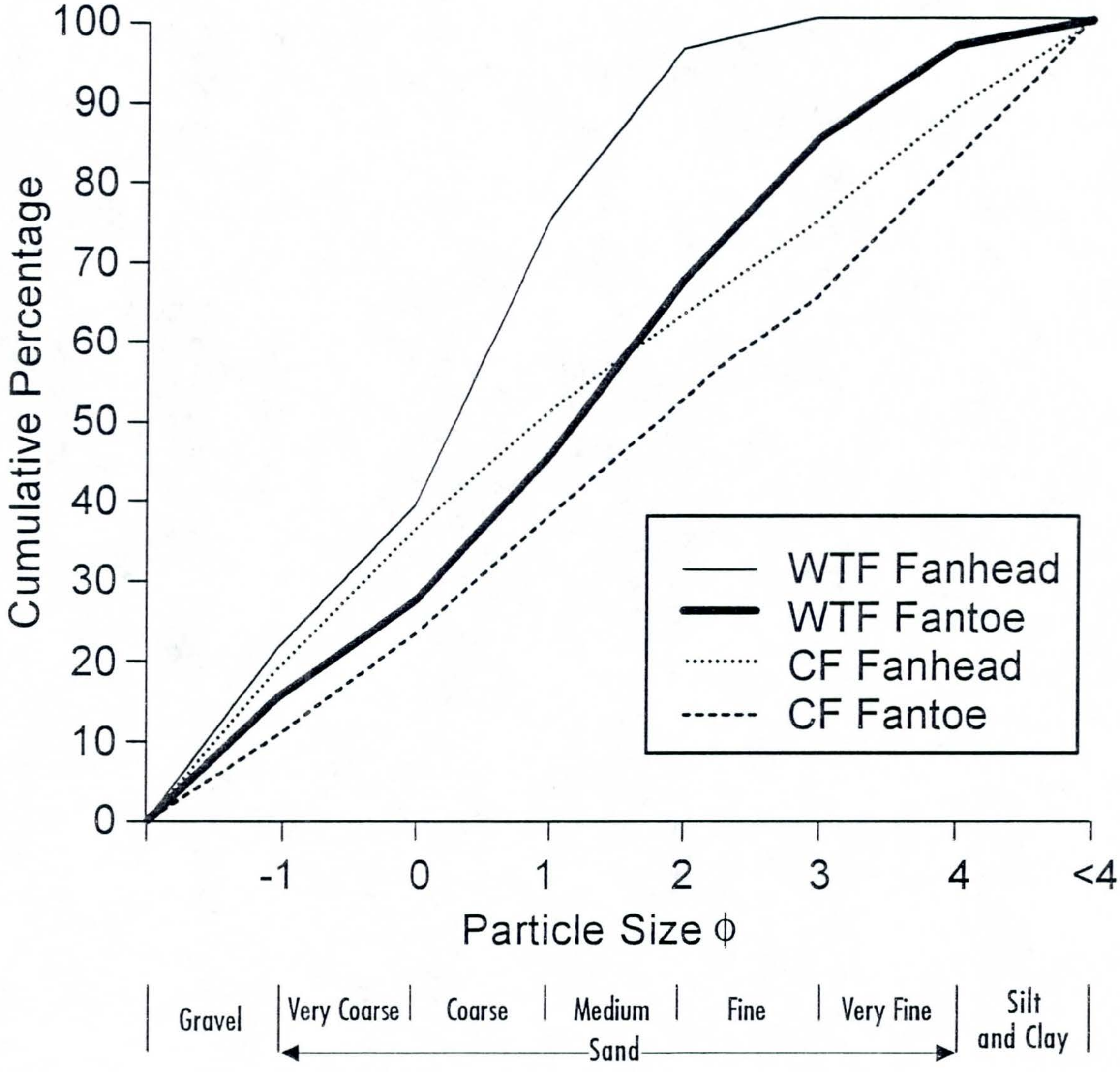


Figure 7. Cumulative grain-size distribution plots of channel-bank sediments from different portions of Cottonwood Fan (CF) and White Tank Fan (WTF).